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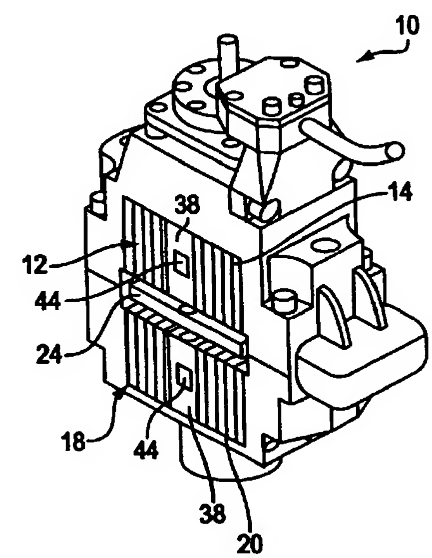
(54) **A method for controlling an armature of a high speed electromagnetic actuator**

(57) A method is provided to control velocity of an armature of an electromagnetic actuator as the armature moves from a first position towards a second position. The electromagnetic actuator includes an electromagnet having a coil and a stator core at the second position. The method includes permitting the armature to move towards the stator core. Magnetic flux in a magnetic circuit created by the armature and electromagnet is determined when the armature is moving toward the stator core. The determined magnetic flux is used as a feedback variable to control energy to the coil so as to control a velocity of the armature as the armature moves towards the stator core.

FIG. 1



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Description

BACKGROUND OF THE INVENTION

[0001] This invention relates to a high-speed, high-force electromagnetic actuator and more particularly, to an electromagnetic actuator for opening and closing a valve of an internal combustion engine wherein a velocity of the armature is controlled upon impact with a stator core of the actuator.

[0002] A conventional electromagnetic actuator for opening and closing a valve of an internal combustion engine generally includes a pair of electromagnets which, when energized, produce an electromagnetic force on an armature. The armature is biased by return springs and the armature is coupled with a gas exchange valve of the engine. The armature is held by one electromagnet in one operating position against a stator core thereof and, by deenergizing the electromagnet, the armature may move via a return spring towards the stator core of the other electromagnet.

[0003] In an attempt to control the landing velocity of the armature at a stator core in an open loop manner, current in the coils of the electromagnets may be controlled based on time. Typically, a peak and hold current is used where the turn-on time of the current is based on the expected arrival time of the armature at a stator core. However, with this approach, the arrival time varies as other system variables change which requires an early turn-on of the "catch current" to guarantee capture of the armature. This may cause excess dissipation in the coils. In addition, the force on the armature increases exponentially as the armature approaches the stator core which causes high impact velocity with attending noise and wear.

[0004] Accordingly, there is a need to provide control of an armature of an electromagnetic actuator to minimize the excess on time of the coils and to control the force on the armature so as to produce a quiet (near zero velocity) landing of the armature against a stator core so as to prevent excessive impact wear on the armature and stator core and to reduce the amount of noise produced by such impact.

SUMMARY OF THE INVENTION

[0005] An object of the present invention is to fulfill the need referred to above. In accordance with the principles of the present invention, this objective is obtained by providing a method to control velocity of an armature of an electromagnetic actuator as the armature moves from a first position towards a second position. The electromagnetic actuator includes an electromagnet having a coil and a stator core at the second position. The method includes permitting the armature to move towards the stator core. Magnetic flux in a magnetic circuit created by the armature and electromagnet is determined when the armature is moving toward the stator core. The determined magnetic flux is used as a feedback variable to control energy to the coil so as to control a velocity of the armature as the armature moves towards the stator core.

[0006] In accordance with another aspect of the invention, a method is provided to control current to a coil of an electromagnetic actuator as an armature of the electromagnetic actuator moves from a first position towards a second position. The electromagnetic actuator includes an electromagnet having a coil and a stator core at the second position. The method includes permitting the armature to move towards the stator core. A peak current is supplied to the coil. Magnetic flux in a magnetic circuit created by the armature and the electromagnet is sensed when the armature is moving toward the stator core. The sensed magnetic flux is used as a feedback variable to control a length of time the peak current is supplied to the coil.

[0007] Other objects, features and characteristic of the present invention, as well as the methods of operation and the functions of the related elements of the structure, the combination of parts and economics of manufacture will become more apparent upon consideration of the following detailed description and appended claims with reference to the accompanying drawings, all of which form a part of this specification.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008]

FIG. 1 is a perspective view of an electromagnetic actuator provided in accordance with the principles of the present invention;

FIG. 2 is a perspective view of a lower electromagnet of the electromagnetic actuator of FIG. 1;

FIG. 3 is a schematic sectional view of the electromagnetic actuator of FIG. 1 shown coupled with a gas exchange valve, with the valve in an open position;

FIG. 4 is a schematic sectional view of the electromagnetic actuator of FIG. 1 shown coupled with a gas exchange valve, with the valve in a closed position;

FIG. 5 is an enlarged schematic illustration of the armature disposed between the two electromagnets of the electromagnetic actuator of FIG. 1;

FIG. 6 is a view of the shaded portion of FIG. 5 showing flux lines and the location of a flux sensor;

FIG. 7 are waveforms of current, flux, position and velocity with respect to an armature of the electromagnetic actuator of the invention operating in an

open loop control mode;

FIG. 8 are waveforms of current, flux and position with respect to an armature of the electromagnetic actuator of the invention showing that flux may be used to control system timing and thus duration of peak current;

FIG. 9 is a block diagram of a control circuit of the electromagnetic actuator of FIG. 1; and

FIG. 10 are waveforms of current, flux, position and velocity of an armature of the electromagnetic actuator of the invention showing flux being controlled to be substantially constant upon landing of the armature.

DETAILED DESCRIPTION OF THE INVENTION

[0009] Referring to FIGS. 1-4, an electromagnetic actuator is shown, generally indicated 10, provided in accordance with the principles of the present invention. The electromagnetic actuator 10 includes a first electromagnet, generally indicated at 12, which includes a stator core 14 and a solenoid coil 16 associated with the stator core 14. A second electromagnet, generally indicated at 18, is disposed generally in opposing relation to the first electromagnet 12. The second electromagnet includes a stator core 20 and a solenoid coil 22 associated with the stator core 20. The electromagnetic actuator 10 includes an armature 24 which is attachable, via shaft 25, to a stem 26 of a gas exchange valve 28 through a hydraulic valve adjuster 27. The armature 24 is disposed generally between the electromagnets 12 and 18 so as to be acted upon by the an electromagnetic force created by the electromagnets. In a deenergized state of the electromagnets 12 and 18, the armature 24 is maintained in a position of rest generally between the two electromagnets 12 and 18 by opposing working return springs 30 and 32. In a valve close position (FIG 2), the armature 24 engages the stator core 14 of the first electromagnet 12.

[0010] To initiate motion of the armature 24 and thus the valve 28 from the closed position into an open position (FIG. 1), a holding current through solenoid coil 16 of the first electromagnet 12 is discontinued. As a result, a holding force of the electromagnet 12 falls below the spring force of the return spring 30 and thus the armature 24 begins its motion accelerated by the return spring 30. To catch the armature 24 in the open position, a catch current is applied to the electromagnet 18. Once the armature 24 has landed at the stator core 20, the catch current is changed to a hold current which is sufficient to hold the armature at the stator core 20 for a predetermined period of time.

[0011] Each of the electromagnets 12 and 18 are identically configured and the structure thereof will be explained with respect to the second electromagnet 18. As best shown in FIG. 2, the stator core 20 of electromagnet 18 includes a lamination stack which is contained in a lower housing 34. The lamination stack comprises plurality of individual laminations 36 stacked alongside a thicker, central lamination 38. The central lamination 38 includes a bore 42 therethrough for receiving shaft 25. The laminations 36 and 38 are preferably composed of a soft magnetic material such as silicon iron. Each lamination 36 and 38 is generally E-shaped defining channels 40 to receive the coil 22 of the electromagnet 18. The individual laminations are preferably joined by a weld, or other suitable method such as by pins or an interlocking arrangement to define the stator core 20.

[0012] In accordance with the principles of the invention, the each of stator cores 14 and 20 includes a flux sensor 44 associated therewith. FIG. 5 is a schematic end view of the electromagnets 12 and 18 which define a magnetic circuit with the armature 24 disposed therebetween. FIG. 6 illustrates the flux lines 46 associated with the shaded portion of FIG. 5 and the location of the flux sensor 44. Thus, the flux sensor 44 is positioned in each stator core 14 and 20 where the flux lines are substantially linear and most uniformly spaced so that the exact location of the flux sensor 44 is less critical. As best shown in FIG. 1, the flux sensor 44 is disposed in the central lamination 38 of each stator core 14 and 20. The flux sensor is preferably a Hall effect sensor, or may be a GMR sensor, eddy current sensor or other sensor which can sense magnetic flux.

[0013] With reference to FIG. 7, in an open loop operation of the actuator 10 including use of the flux sensor 44, to initiate movement of the armature and thus move the valve 28 from a valve open position shown in FIG. 1 to a valve closed position as shown a FIG. 2, full voltage is applied to the first solenoid coil 16 at the beginning of armature stroke at time To. Simultaneously, power is removed from the second solenoid coil 22 to release the armature 24 from the second stator core 20. Once the armature 24 is moving, voltage at the solenoid coil 16 is removed to permit the armature 24 to travel as a spring mass system under simple harmonic motion until it is near closing. At time T2, full coil voltage is applied to the coil 16 to initiate a catch current phase. Finally, at a time T3, the coil voltage on the receiving coil 16 is reduced to a value sufficient to hold the armature 24 to the stator core 14 against the bias of return spring 30. As noted from FIG. 7, current is brought to the peak value early and held there until R3. Further, the output of the flux sensor 44 is a function of the flux in the air gap between the armature 24 and stator core 14. As the armature 24 approaches the stator core 14, the output of the flux sensor 44 rises rapidly in the area of interest (near the point of impact) and is relatively free of noise. Thus, the output form the flux sensor 44 can be used to determine the position of the armature 24.

[0014] In accordance with the invention, to reduce

the excess dissipation in the coils 16 and 22, the flux as sensed by the flux sensor 44 may be used to control the length of time the coil 16 or 22 is at a peak current during the catch current phase. With reference to FIG. 8, using flux control, the current remains at peak for a short period of time. This occurs since the signal 48 from the flux sensor 44 may be fed back to a microprocessor 50 controlling the basic system timing (FIG. 9). By having cycle by cycle information of the transition times of the armature 24, the microprocessor 50 can calculate the optimal turn on times for the coils 16 and 22 and thus reduce the power dissipation.

[0015] In accordance with another aspect of the invention, feedback is provided to increase the robustness of the armature control in order to reduce the force of impact of the armature against the stator core.

[0016] The invention provides a proportional control loop based on flux sensed by the flux sensors 44. Thus, in accordance with the invention, coil 22 is connected electrically to a programable driver current controller 52 (FIG. 9). Description of operation is made with regard to coil 22 and stator core 20 of the second electromagnet 18. It can be appreciated that this description applies to the operation of the first electromagnet 12 as well. As is commonly employed, a current level of a sufficiently large value is initially commanded in the coil 22 to achieve rapid movement of the armature 24 through its stroke. The current level is then reduced to a value just enough to hold the armature 24 in contact with the associated stator core 20 until the end of a desired cycle for the actuator 10 at which time current is reduced zero.

[0017] FIG. 10 shows waveforms of an actuator of the invention including velocity and position of the armature 24, flux as determined by the flux sensor 44, and current of coil 22. The flux is used to control a catch current supplied to the coil 22 of the actuator 10. Thus, the flux is connected back through a proportional control loop such that the flux is forced to a constant value between R2 and R3, rather than increasing exponentially as in an open loop system. The coil current is controlled by the loop so as to maintain a substantially constant flux until the microprocessor timing control switches to a "hold" mode of operation (provides a hold current). With the above described control, the velocity waveform in FIG. 8 illustrates the landing velocity of the armature 24 to be near zero at or near R3. The current waveform is also shown in FIG. 8 and the dip 54 in the current occurs when the armature 24 impacts with the stator core 20. Finally, the position wave shape in FIG. 8 indicates the movement of the armature 24 from an initial position to a landing position at a stator core 20.

[0018] The reason for interfacing directly into the current control circuitry is because the microprocessor 50 can only command two current levels which is insufficient for true proportional control. If the control from the microprocessor were made through a high speed D to A converter and the microprocessor was upgraded to a digital signal processor, or other processor capable of real time control, then the proportional control loop could be closed through the processor.

[0019] It is noted that the flux is generally linear near impact of the armature 24 with a stator core 20. The flux in this region between R2 an R3 is set by the catch current and is substantially constant. Thus, as the armature 24 is approaching landing, the flux is low, reducing the magnetic force from the receiving stator core and coil causing the velocity of the armature 24 to approach zero. At T3, the flux is no longer inhibited and the armature 24 is held against the stator core 20.

[0020] The final value of flux, which is the force on the armature, is set at T3 by the hold current so as to just exceed the opposing spring force created by spring 32. This permits rapid release of the armature 24 at the beginning of the next stroke of the valve 28.

[0021] The foregoing preferred embodiments have been shown and described for the purposes of illustrating the structural and functional principles of the present invention, as well as illustrating the methods of employing the preferred embodiments and are subject to change without departing from such principles. Therefore, this invention includes all modifications encompassed within the spirit of the following claims.

Claims

1. A method of controlling velocity of an armature of an electromagnetic actuator as the armature moves from a first position towards a second position, the electromagnetic actuator including an electromagnet having a coil and a stator core at said second position, the method including:

   permitting said armature to move towards said stator core;
   determining magnetic flux in a magnetic circuit created by said armature and electromagnet when said armature is moving toward said stator core; and
   using the determined magnetic flux as a feedback variable to control energy to said coil so as to control a velocity of said armature as said armature moves towards said stator core.

2. The method according to claim 1, wherein controlling energy to said coil includes applying a catch current to said coil when said armature is approaching said stator core, said catch current being controlled based on a value of said magnetic flux.

3. The method according to claim 1, wherein determining said magnetic flux includes providing a flux sensor to sense said magnetic flux.

4. The method according to claim 3, wherein said flux sensor is a Hall effect sensor.

5. The method according to claim 1, wherein the velocity of said armature is controlled so as to be substantially zero as said armature lands at said stator core.

6. The method according to claim 5, wherein once said armature lands at said stator core, said catch current is changed to a current sufficient to hold said armature at said stator core.

7. The method according to claim 1, wherein current to said coil is controlled so that said magnetic flux is substantially constant prior to said armature landing at said stator core.

8. The method according to claim 1, wherein said magnetic flux is determined by a flux sensor mounted at said stator core.

9. An electromagnetic actuator comprising:

an armature movable between first and second positions;
an electromagnet having a coil and a stator core at said first position, and
control structure to control movement of said armature, said control structure being constructed and arranged to sense magnetic flux created by a magnetic circuit defined by said armature and said electromagnet when said armature is approaching said stator core, and to use said sensed magnetic flux as a feedback variable to control energy to said coil and control a velocity of said armature as said armature moves towards said stator core.

10. The electromagnetic actuator according to claim 9, wherein said control structure includes a flux sensor to sense said magnetic flux.

11. The electromagnetic actuator according to claim 10, wherein said flux sensor is a Hall effect sensor.

12. The electromagnetic actuator according to claim 9, wherein said control structure is constructed and arranged to control a velocity of said armature to be substantially zero upon landing of said armature at said stator core.

13. The electromagnetic actuator according to claim 10, wherein said flux sensor is disposed in said stator core at a position where flux is substantially linear and uniform.

14. The electromagnetic actuator according to claim 13, wherein said stator core comprises a central lamination and a plurality of laminations stacked on opposing ends of said central lamination, said central lamination having a thickness greater than a thickness of each lamination of said plurality of laminations, said flux sensor being disposed in said central lamination.

15. The electromagnetic actuator according to claim 14, wherein each of said plurality of laminations and said central lamination is generally E-shaped defining a pair of channels to receive said coil.

16. A method of controlling current to a coil of an electromagnetic actuator as an armature of the electromagnetic actuator moves from a first position towards a second position, the electromagnetic actuator including an electromagnet having a coil and a stator core at said second position, the method including:

permitting said armature to move towards said stator core;
supplying a peak current to said coil;
sensing magnetic flux in a magnetic circuit created by said armature and said electromagnet when said armature is moving toward said stator core; and
using the sensed magnetic flux as a feedback variable to control a length of time said peak current is supplied to said coil.

17. The method according to claim 16, wherein said magnetic flux is sensed by a flux sensor.

18. The method according to claim 17, wherein said flux sensor is a Hall effect sensor.

19. The method according to claim 116, wherein said magnetic flux is determined by a flux sensor mounted in said stator core.

FIG. 1

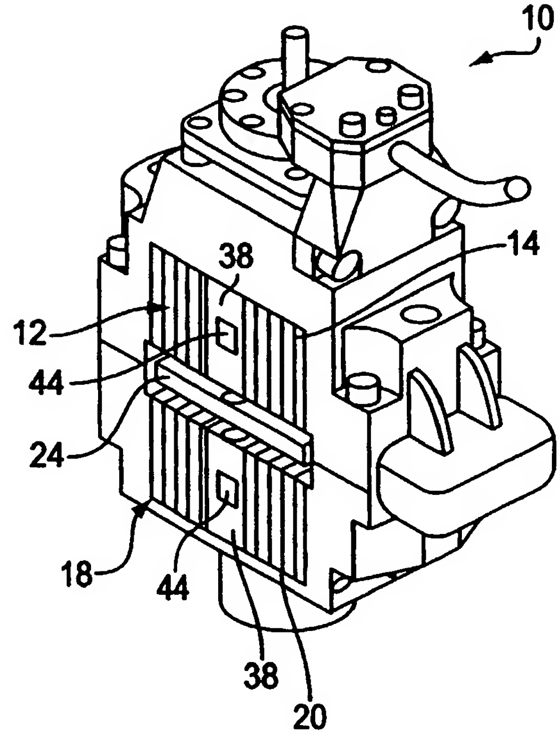
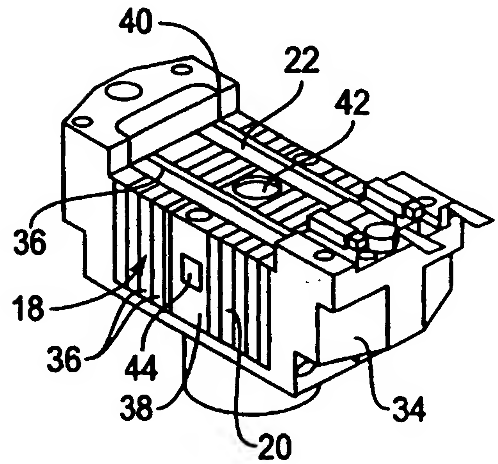


FIG. 2



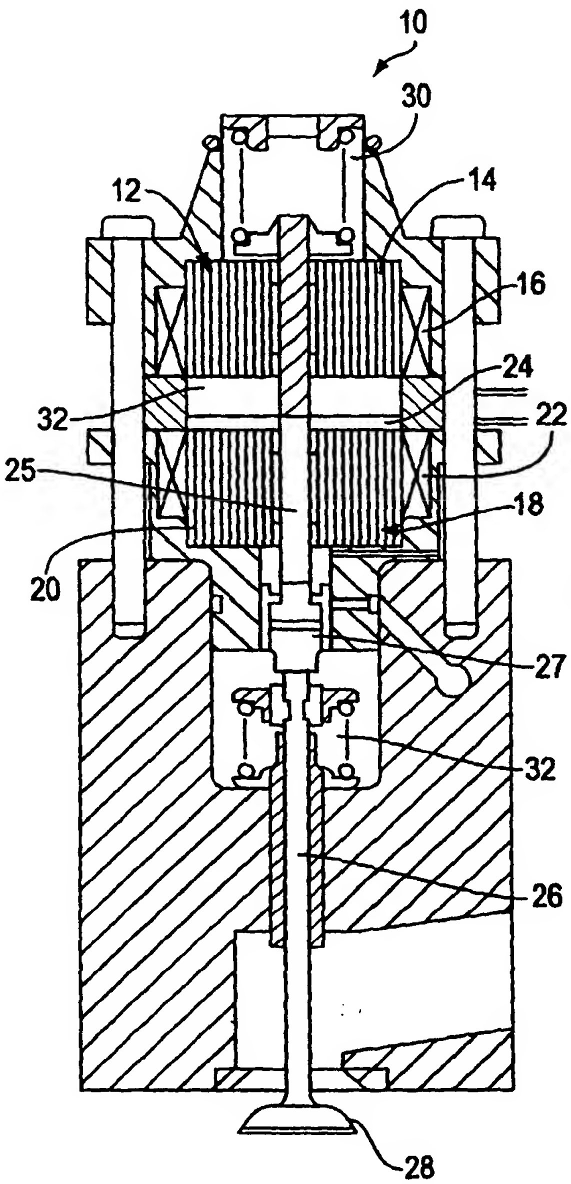

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FIG. 3

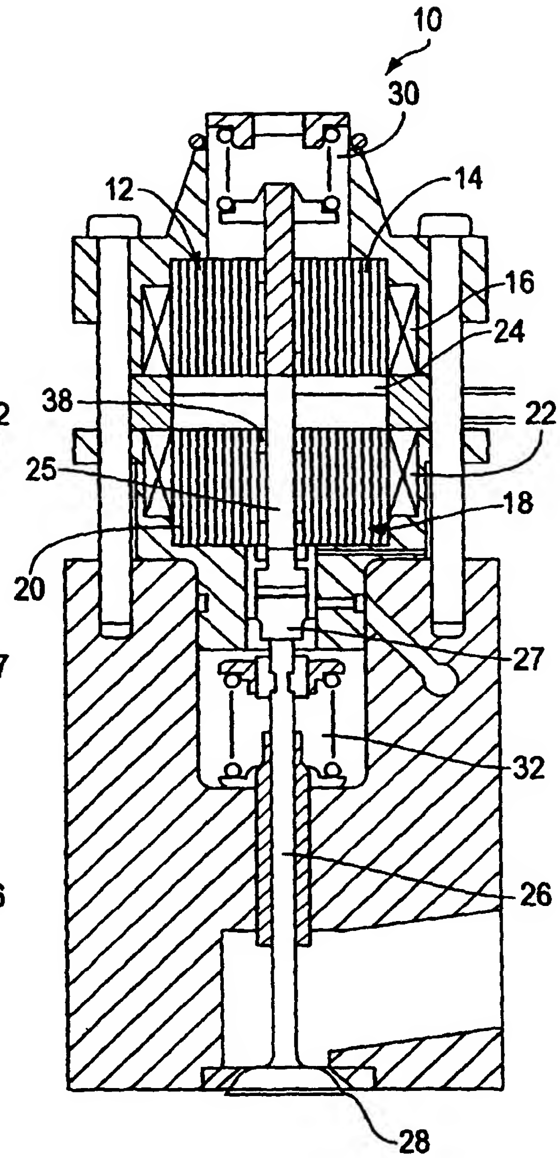
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FIG. 4

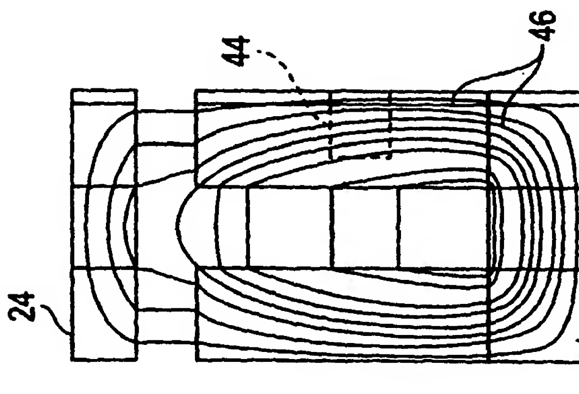


FIG. 6

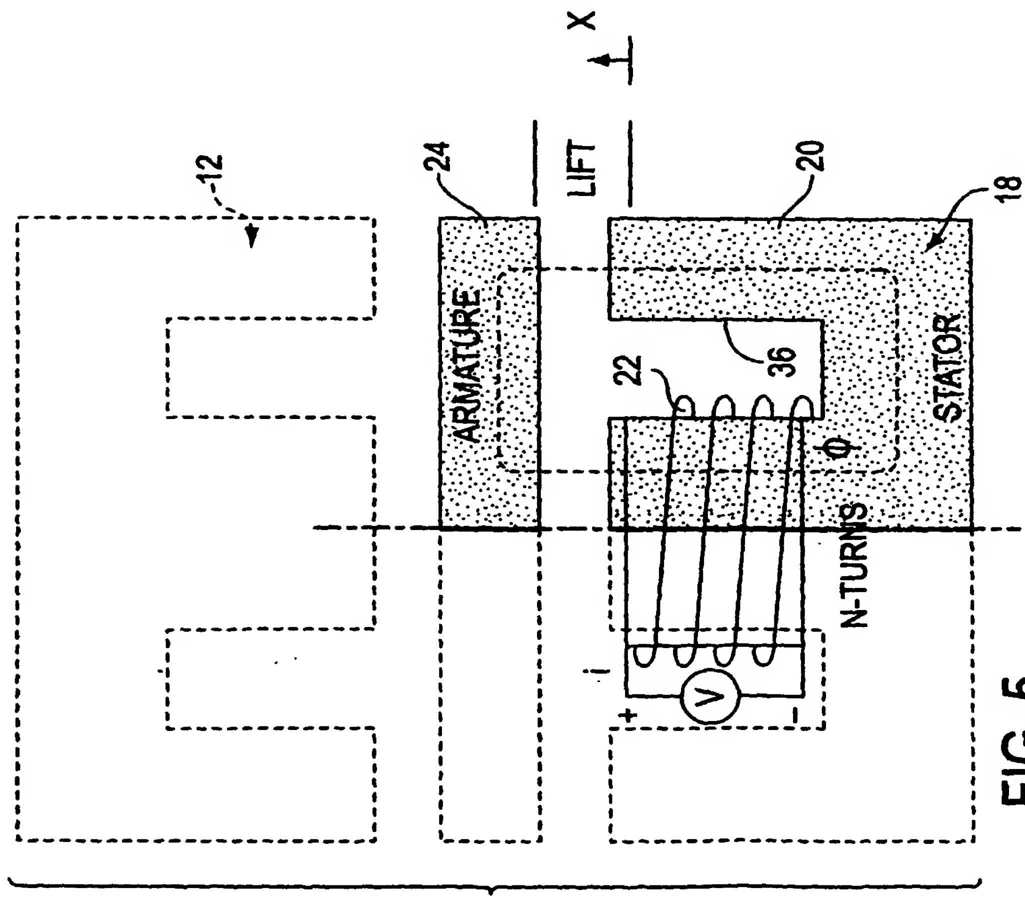


FIG. 5

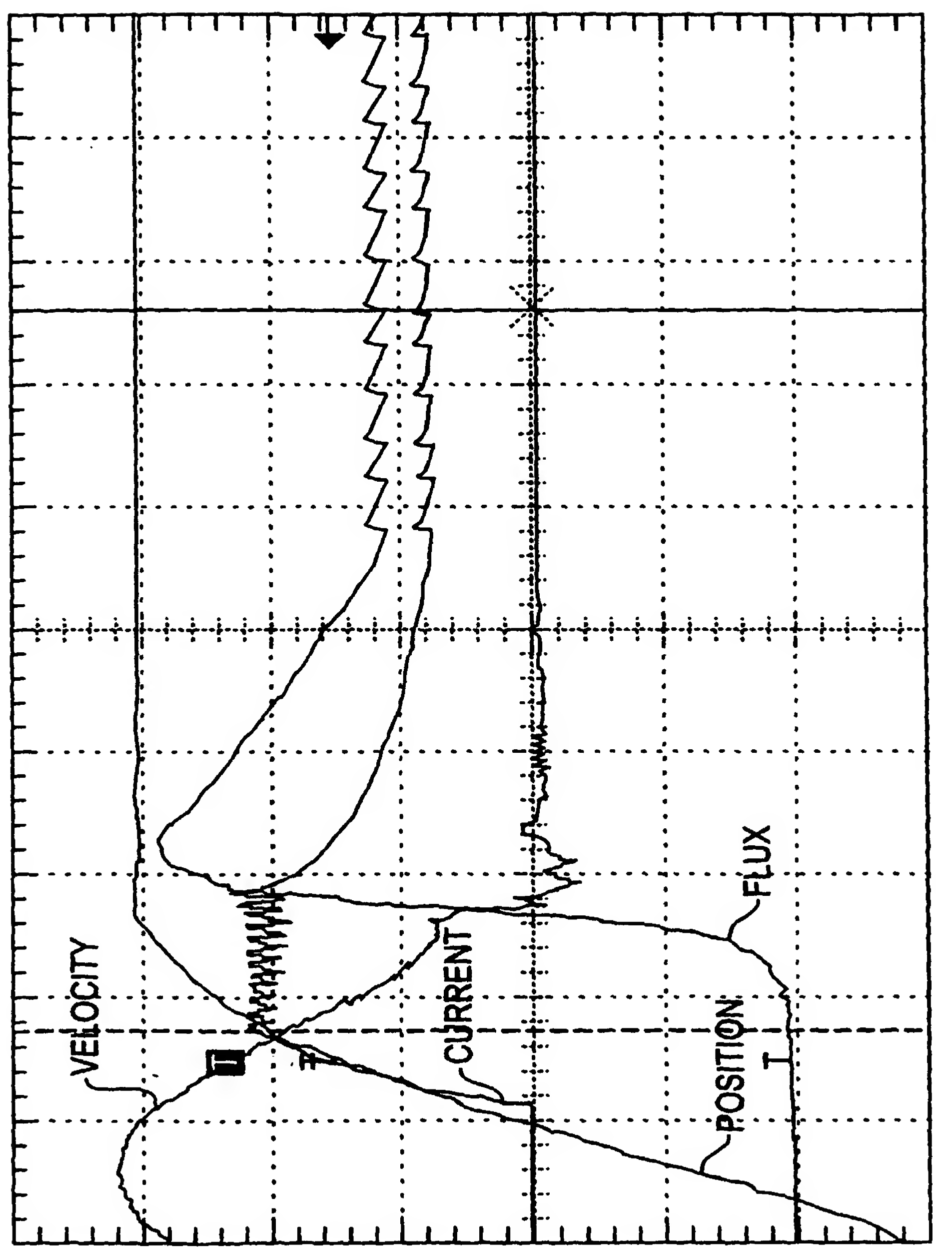
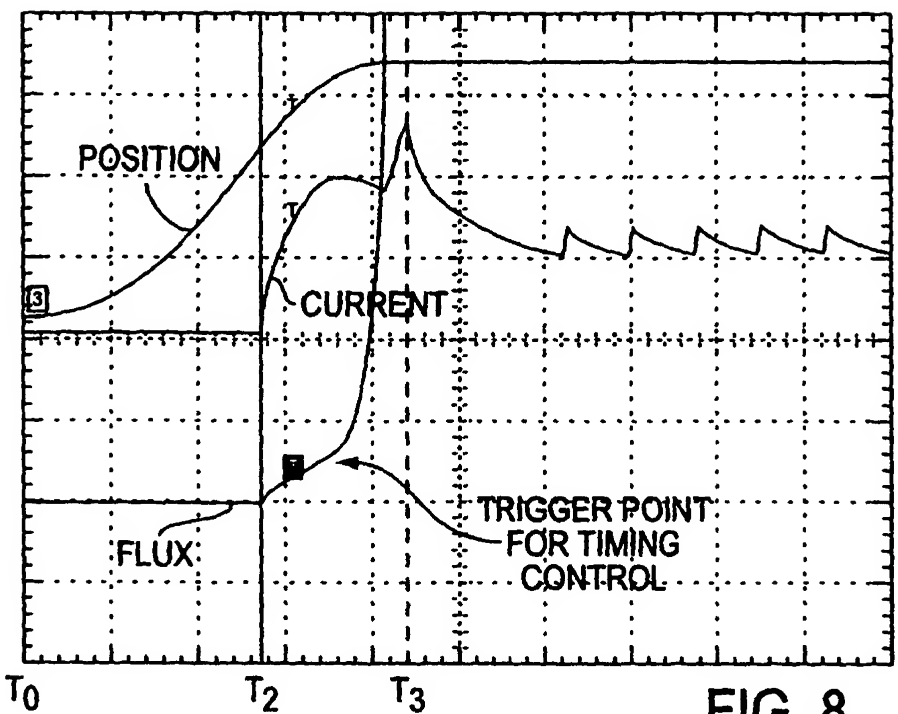


FIG. 7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TRIGGER POINT
FOR TIMING
CONTROL
FLUX
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T_2
T_3

FIG. 8

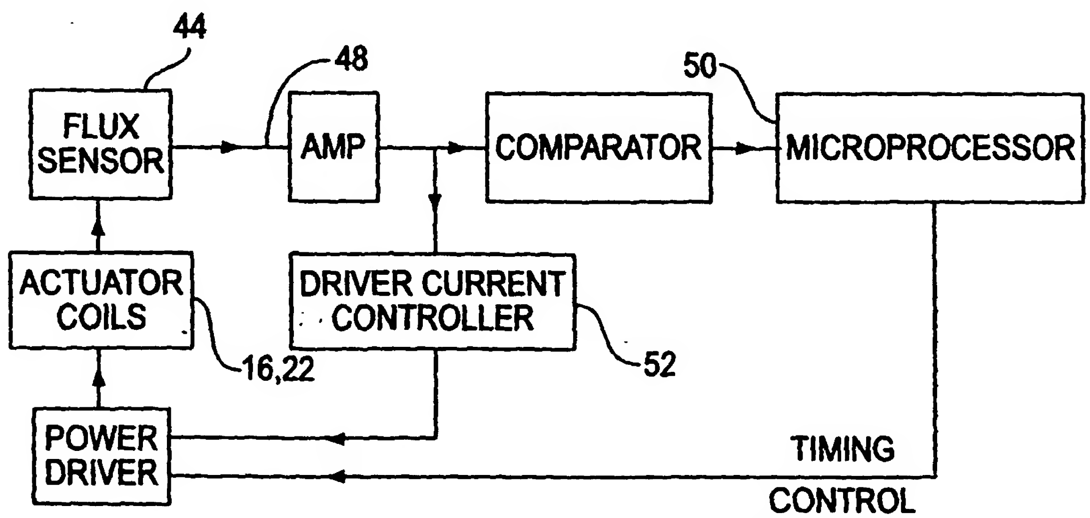
44
48
50
FLUX SENSOR
AMP
COMPARATOR
MICROPROCESSOR
ACTUATOR COILS
DRIVER CURRENT CONTROLLER
16,22
52
POWER DRIVER
TIMING
CONTROL

FIG. 9

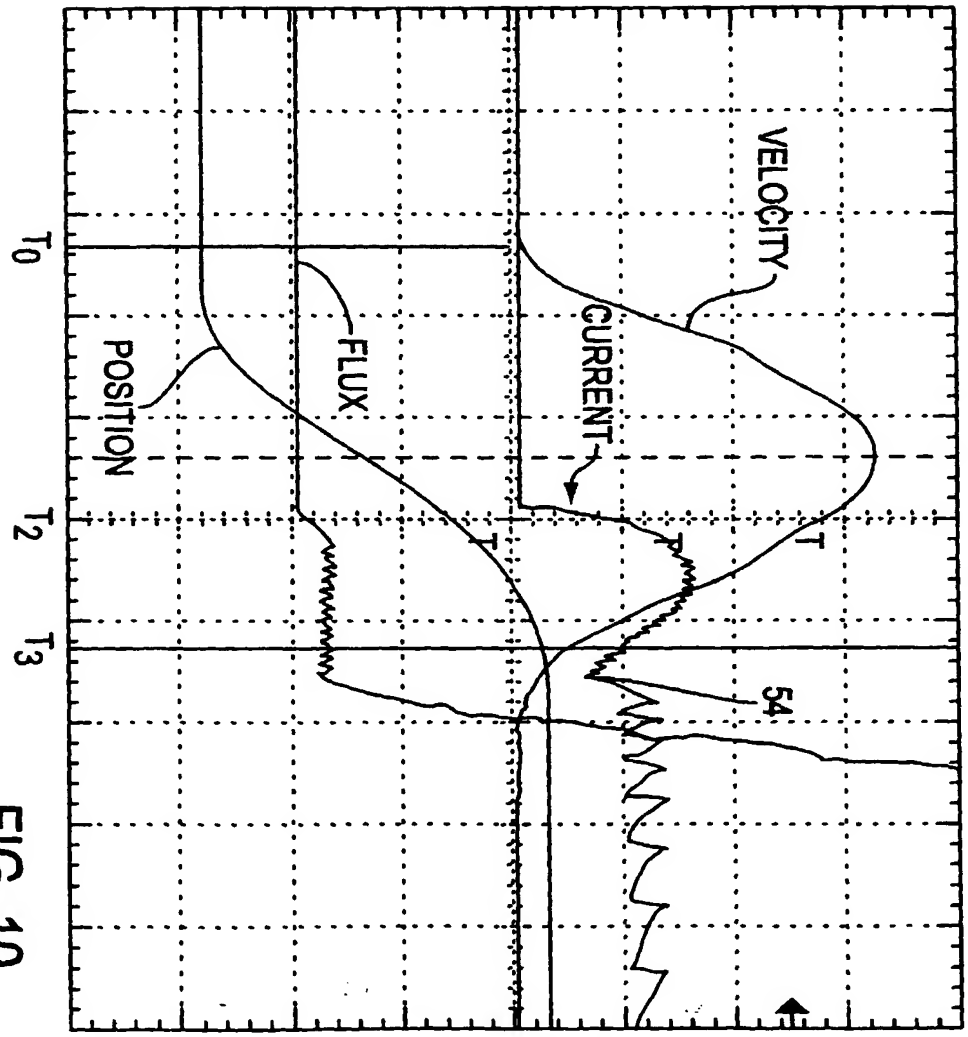

FIG. 10

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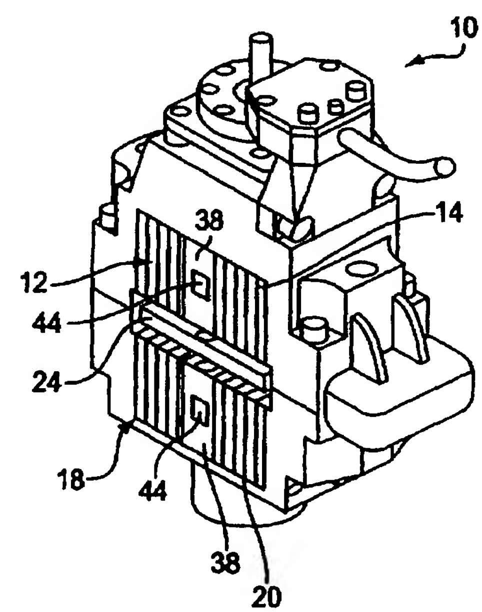
FIG. 1



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European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 00 10 3929

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
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			TECHNICAL FIELDS SEARCHED (Int.Cl.7)
			H01F F01L

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	2 October 2001	Durville, G

CATEGORY OF CITED DOCUMENTS

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E : earlier patent document, but published on, or after the filing date
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ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO.

EP 00 10 3929

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The members are as contained in the European Patent Office EDP file on
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02-10-2001

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